

Additive manufacturing tooling for the automotive industry

R. Leal^{1,2} · F. M. Barreiros¹ · L. Alves¹ · F. Romeiro¹ · J. C. Vasco¹ · M. Santos² · C. Marto³

Received: 22 December 2016 / Accepted: 1 March 2017 / Published online: 16 March 2017
© Springer-Verlag London 2017

Abstract Automotive industry faces new challenges every day, new design trends and technological deployments from research push companies to develop new models and facelifts in short term, requiring new tools or tool reshaping. Concerning the current world economic scenario, decreasing time for tooling up becomes as important as decreasing time-to-market. Such scenario opens up the horizons for new manufacturing approaches like additive manufacturing, in this case, applied for tooling up a stamping process on the automotive industry for the production of body panels. This approach enables the manufacturing of stamping inserts using similar high performance alloy steel as in conventional tooling, therefore, without losing tool mechanical properties. The stamping tools produced were tested by an automotive company in order to determine tool behaviour under real operating conditions, considering the high level demands of the stamping process. The results obtained enabled to conclude that metal additive manufacturing provided tools for the stamping process with excellent performance with a significant decrease on time-to-tooling.

Keywords Additive manufacturing · Automotive industry · Time-to-tooling · Stamping

✉ J. C. Vasco
joel.vasco@ipleiria.pt

¹ School of Technology and Management, Polytechnic Institute of Leiria, Leiria, Portugal

² Volkswagen Autoeuropa, Toolshop, Palmela, Portugal

³ BBE Engineering Lda, Marinha Grande, Portugal

1 Introduction

The automotive industry is one of the most competitive business areas where time-to-market decrease plays an important role as well as the decrease of time-to-tooling, requiring new approaches to flexible manufacturing systems (FMS) such as additive manufacturing (AM) that enable the flexible production of customised products without significant impact on costs and lead time [1, 2]. Automotive companies are developing new models and facelifts every day, pushed by new design trends and technological evolution where aesthetics, aerodynamics, safety and weight reduction of the vehicle are key issues [3]. Therefore, new tools or tool reshaping for new components is required, for body panels or other technical components. Additive manufacturing has proven to be one of the most promising answers concerning rapid responses to market requirements. In particular, metal additive manufacturing provides the same design freedom along with suitable materials for high-demanding applications [1, 2, 4–6].

The demands for automotive parts produced by the stamping process increased significantly on the last decades, currently going over 100 million parts per year. Applications for the automotive industry stamped parts are chassis components, such as the A-pillar, B-pillar, bumper, roof rail, rocker rail and tunnel. The sheet thickness of these parts may vary between 1.0 and 2.5 mm [7].

This study aims the use of direct metal laser fabrication, for subsequent selection of one of the variants presented. Within the metal AM processes addressed, the chosen was a powder bed fusion process, the fifth category on the ASTM F42 and ISO/TC 261 ongoing standards [4, 5, 7]—the direct metal laser sintering (DMLS)—technology owned by EOS GmbH (Germany). This is a layer-by-layer technology that fuses metal powder into a solid piece by melting it

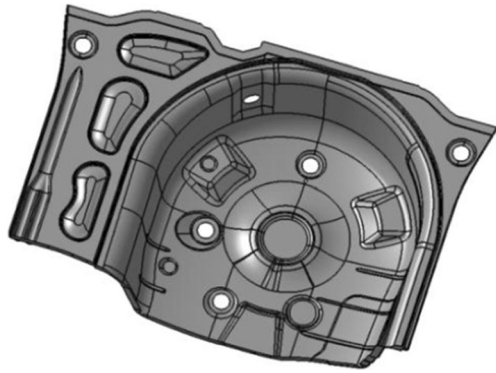


Fig. 1 Body panel to be produced

locally using the focused laser beam. The process uses a 3D model based on an STL file which is sliced into the layer thickness required to be built on the machine. The part is properly oriented inside the building chamber, enabling to build more parts at the same time and/or the best building orientation. Structural supports are added as appropriate [4, 5, 8, 9]. The DMLS machine (EOSINT M270) uses a high-powered Yb-fibre optic laser. Inside the building chamber, there is a powder dispensing platform and a building platform along with a recoating system used to feed new powder to the building platform [9]. This technology has been studied extensively [10–13] and it was used in the production of stamping tool inserts and afterwards, assembled on stamping tools for the automotive industry. Since this study was promoted by Volkswagen Autoeuropa, Toolshop, a comparison was carried out considering the manufacturing time and relative costs as well as the overall behaviour under production conditions between the different tooling inserts provided by conventional and additive manufacturing processes.

2 Conventional versus additive tooling: materials and processes

The comparison between the conventional and additive manufacturing approaches for the stamping tool industry cannot be dissociated from the materials used and the several subsequent manufacturing stages required, such as machining, finishing, thermal treatment and assembly on the stamping tool [14].

Conventional stamping industry for the automotive domain uses 1.2379 and 1.2358 steel. Typically, this material is submitted to thermal post-processing. The 1.2379 has a heat treatment at 1060 °C with the first tempering stage at 520 °C and

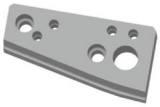




the second stage at 200 °C, while the 1.2358 steel has a heat treatment at 960 °C with two tempering stages at 200 °C [15]. Concerning the conventional manufacturing approach, two solutions were considered: (1) the machining of the tool inserts directly from laminated steel and (2) the use of the lost foam casting process to obtain near net-shape geometries for each tool insert and the correspondent finishing process.

In metal additive manufacturing, the EOS Maraging Steel MS1 from EOS GmbH has a chemical composition corresponding to the 1.2709 steel (X3NiCoMoTi 18-9-5), providing the most similar properties to the material used in conventional tools inserts in the automotive industry [16].

The additive manufacturing approach consisted on the use of the DMLS technology, in this case it was used an EOSINT M270 (EOS GmbH, Germany), enabling the tool inserts to be built directly from the 3D CAD data. In order to evaluate the manufacturing time and the impact on tool costs, additive manufacturing inserts were produced to be used on a stamping tool for the body panel shown in Fig. 1.

In this study, five inserts from a body panel stamping tool were chosen, three of which are die cutting inserts. All the five tool inserts are presented in Table 1, where its geometry and maximum dimensions are shown.

Table 1 Tool inserts

Tool insert type	Geometry	Overall dimensions [mm]
Calibration insert		205.00 x 97.25 x 56.43
Cutting insert 5		125.00 x 115.00 x 58.71
Cutting insert 25		200.00 x 135.00 x 64.95
Cutting insert for round hole		130.61 x 100.00 x 71.28
Blankholder insert		95.00 x 44.51 x 43.90

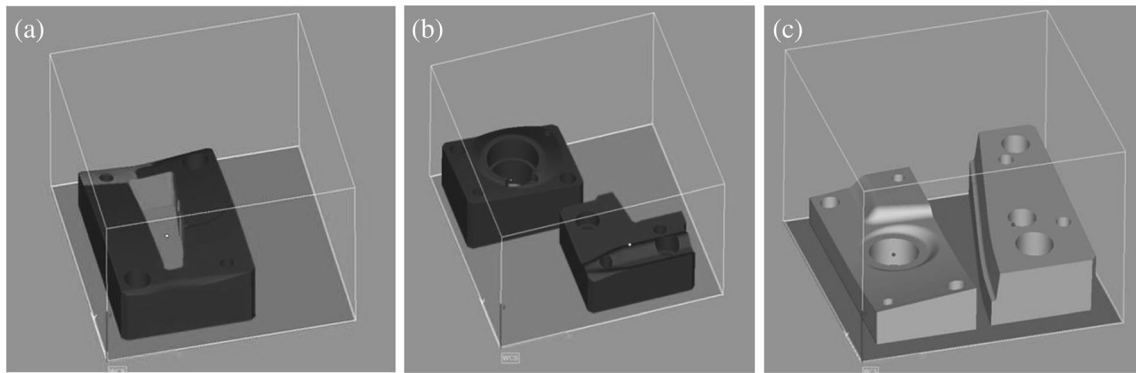


Fig. 2 Inserts orientation and position inside the building chamber

3 Manufacturing of tool inserts

Typically, in the automotive stamping industry, blank inserts are laminated, then cut to near net-shape, thermal treated to provide the required behaviour and finally, surfaces are finished to achieve the desired surface quality and meet the final tolerances. In the particular case of automotive industry, tool inserts may be produced through casting processes using lost foam models that need to be manufactured previously. Such approach eliminates the two initial phases, prior to thermal treatment, although outsourcing may be required for the whole casting process, with a direct and quite significant impact on final tool lead time.

As mentioned previously, the DMLS technology was used with the desired intent of eliminating some of these variants, decreasing the manufacturing complexity and to streamline the supply chain [1, 6].

The parts were setup on the platform according to its dimensions and building chamber dimensions. The EOSINT M270 has an effective building chamber of 250 × 250 × 215 mm, which requires the largest part—cutting insert 25—to be built separately (Fig. 2a) while the remaining tool inserts were grouped in two other building operations. Figure 2b depicts the hole cutting insert and the cutting insert 5. Figure 2c shows the blankholder insert and the calibration insert. This setup enabled parts to be properly oriented in order to minimise build time and resources.

The processing parameters used on the EOSINT M270 for the tool inserts production are shown in Table 2.

Parameter	Value
Building speed [mm ³ /s]	3
Layer thickness [μm]	40
Laser power [W]	200

Table 2 DMLS processing parameters

4 Tool inserts post-processing

The surface finishing on products of the metal additive manufacturing processes such as DMLS, typically require suitable post-processing operations to fully prepare the part for its final application [17]. Despite the several in-process monitoring techniques available on commercial AM equipment to be used during processing [10, 13, 17], problems on AM parts may arise, such as the elevated edges effect and changes on microstructural features

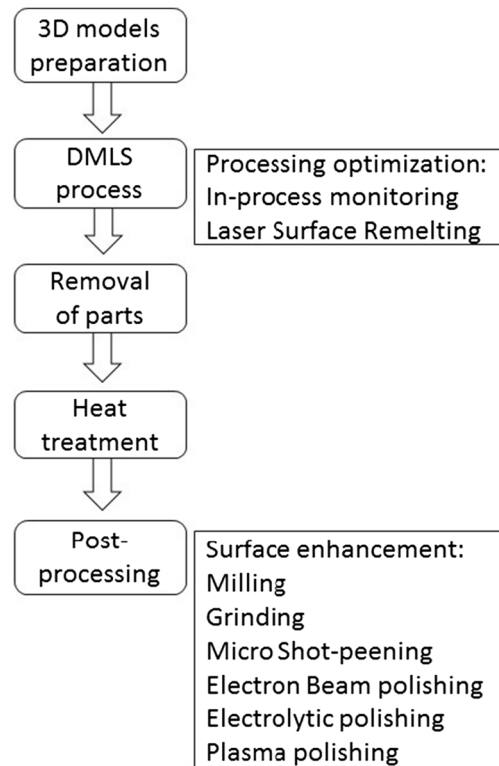
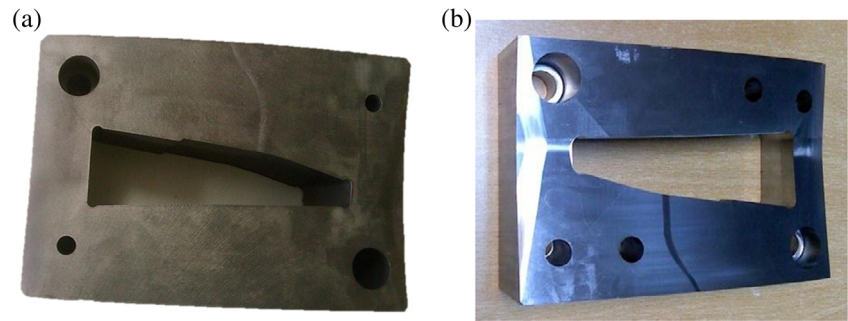


Fig. 3 Typical workflow for DMLS products

Fig. 4 Cutting tool after the DMLS process (a) and after surface polishing (b)



[12, 18]. Concerning surface roughness, significant improvements have been obtained using laser surface remelting, although it may increase the building time [19]. Featuring all these issues, it is mandatory to use the most adequate post-processing operations, for the final part's application. These post-processing operations are presented on the workflow of DMLS products (Fig. 3) and may include mechanical machining and/or grinding, micro shot-peening as well as several polishing procedures [20].

After production, the tool inserts were heat treated in vacuum at 490 °C for 6 h and then air-cooled, according to EOS GmbH recommendations. Also, they were subjected to a surface polishing procedure to ensure the roughness usually required for industrial practice, in this particular case, for the automotive industry ($R_a \approx 0.1\text{--}0.3 \mu\text{m}$) [21]. Surface finishing evaluations after the polishing procedure were carried out with a Mahr Perthometer M2, used directly on the tools inserts produced. Figure 4a, b shows the cutting insert 25 after production and after the surface polishing procedure, respectively. After finishing, the measured surface roughness (R_a) was $0.07 \pm 0.01 \mu\text{m}$ for cutting inserts without thermal treatment and $0.09 \pm 0.01 \mu\text{m}$ after thermal treatment.

Concerning surface hardness, measurements were carried out on a microhardness tester SHIMADZU HMV-2, using a test load of 9807N for 30 s, according to ISO 6507. Considering the physical limitations of the microhardness tester concerning the part's minimum height, only some of the tool inserts were tested. However, the measurements were considered as representative for all inserts, since the production, thermal treatment and surface finishing procedures were identical. Therefore, hardness measurements were obtained, witnessing a significant increase on surface hardness from $38\text{HRC} \pm 0.4$ after the DMLS process to $57\text{HRC} \pm 0.9$ after thermal treatment.

4.1 Costs and lead time

The trade-off between the direct costs of the tool inserts produced and the lead time for each manufacturing

approach was evaluated to provide critical decision factors for the best suited solution. Figure 5 shows the relative positioning for each manufacturing approach, concerning these two variables,

As expected, both manufacturing approaches stand out concerning costs and lead time. Costs for additive manufacturing are significantly higher due to the costs of metal powder and processing equipment. On the other hand, the lead time gain is significant, approximately 35% less than the second fastest manufacturing approach. To fully understand the reasons for such positioning, Figs. 6, 7, 8 depict the cost breakdown for each manufacturing approach.

From the cost breakdown analysis, it is noticeable that the highest share for each manufacturing approach is always related to the main processing operation, regardless of its nature. The share discrepancies on other operations such as 3D scanning and thermal treatment are neglectable since the costs were obtained from different service providers. The conventional manufacturing based on the lost foam process is the overall most time-consuming, comprising more operations than any other process and it will be established as the reference for future

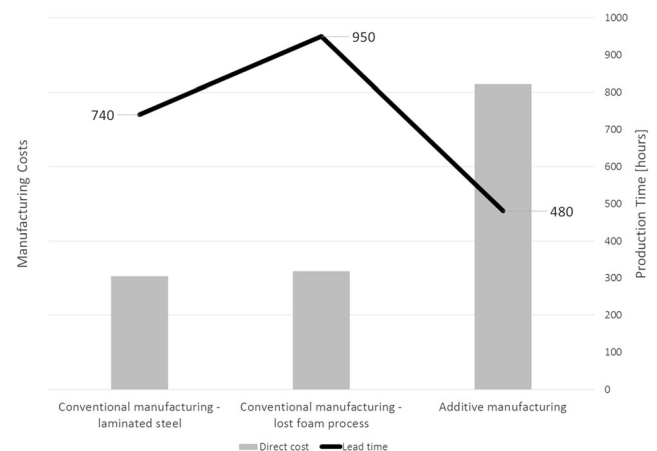


Fig. 5 Relative positioning for each manufacturing approach

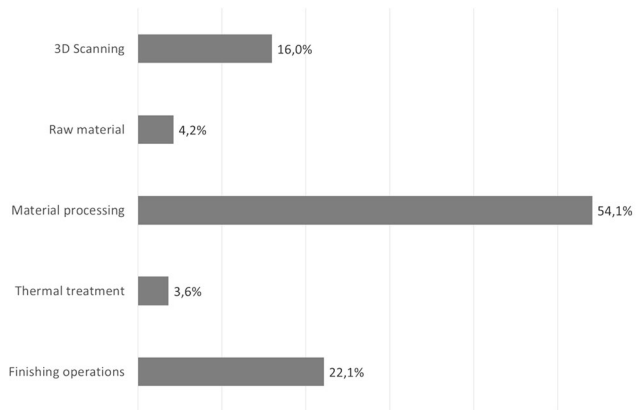


Fig. 6 Cost breakdown for conventional manufacturing from laminated steel

comparison between the manufacturing processes in study.

4.2 Economic impact

The selection of the manufacturing process with the shortest lead time, despite the direct costs involved, could provide an economic benefit as well as a technical advantage. Considering the added value of the parts produced and the production time gained, the break-even point is achievable quite earlier on high series production and therefore, the option for additive manufacturing is advantageous [22]. However, unlike many other industries, where such advantage could provide an early product positioning on the market, the reengineering iterations on body panels or many other sheet metal components before a new vehicle enters the market, causes the automotive industry to take advantage of this time gain quite differently. In fact, the establishment of rigid milestones to define the introduction of a new vehicle inhibits the typical use of an early time gain, since tooling reengineering is often required. Thus, the advantage for the automotive industry might not be the early entry on production of the stamped parts, enabled by a shorter time-to-tooling. On the other hand,

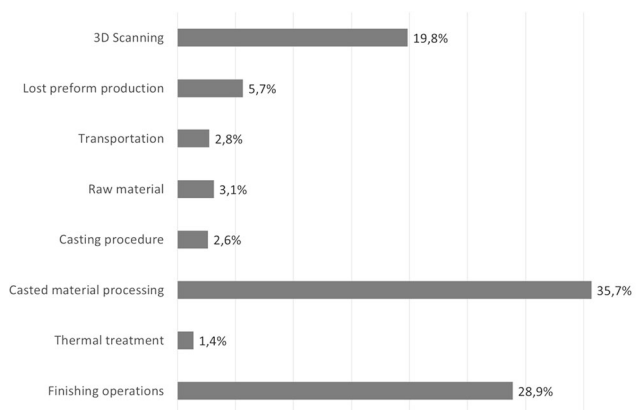


Fig. 7 Cost breakdown for conventional manufacturing from lost foam process

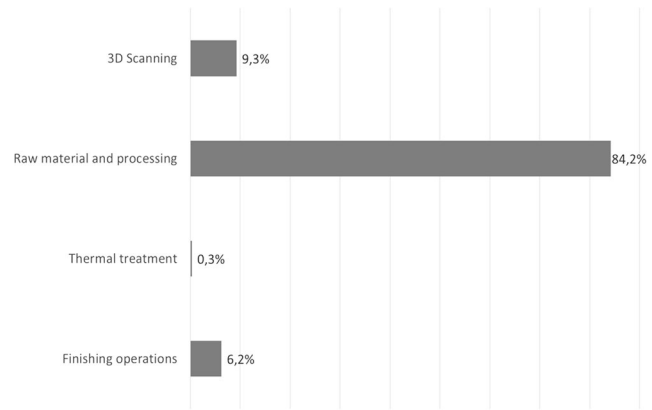


Fig. 8 Cost breakdown for additive manufacturing

another significant advantage is to enable as many as possible design iterations or tool reengineering before the production of the stamping tools, dramatically reducing reengineering costs. Figure 9 shows the time available for tool reengineering, setting the lost foam process as the reference since it has the longest lead time.

Although it is less significant, tool manufacturing from laminated steel also exhibits time available for tool reengineering (210 h), using the longest lead time as reference. The same analysis for additive manufacturing enables a significant delay on the production of stamping tools if required, enabling 470 h available for tool reengineering. Reengineering costs are significantly higher on later phases of a project and may require deep tool changes or even the total redesign of the tool.

Another economical aspect of the additive manufacturing approach relates to tool life. The typical demands for a stamping tool could launch some doubts on the behaviour of tool inserts produced by the DMLS process. However, tool inserts were monitored every tool setup and their performance was not compromised when compared to conventional tooling, by achieving over a million hits for each tool insert during the entire production set.

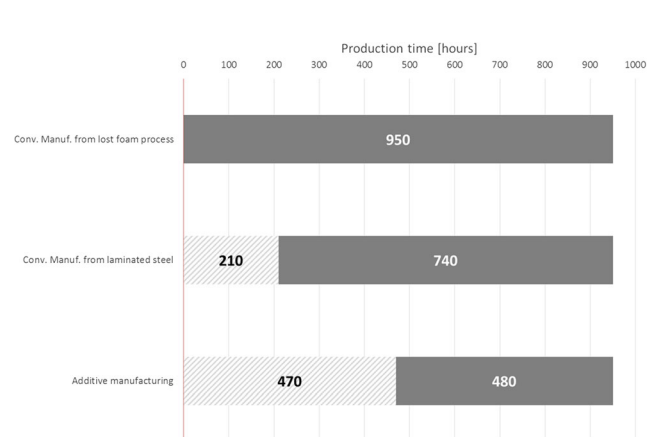


Fig. 9 Tool reengineering time available

5 Conclusions

The comparison between the additive and conventional manufacturing provided suitable indicators for future process selection for the stamping tools manufacturing, enabling better quality decisions concerning the trade-off between manufacturing costs and time-to-tooling.

The shorter lead time provided by additive manufacturing proved to be the key decision factor, enabling tool production in due time, considering the rigidity of the milestones imposed on the automotive industry.

Cost breakdown analysis shows that, despite the higher processing costs, additive manufacturing vs. the lost foam process requires significantly less operations, therefore, minimising internal process logistics.

The analysis of lead times show that conventional manufacturing from laminated steel offers a good compromise with costs, however, it takes 260 additional hours to produce the same tool inserts.

Stamping tool inserts for the automotive industry were produced and tested successfully, achieving similar performance levels as conventional tools.

This application does not require the production of complex geometries that DMLS is capable of. However, considering the type of mechanical demands, some tool inserts could have their geometry optimised, enabling less volume for the tool and, therefore, less building time and manufacturing costs, improving the use of this technology.

References

- Weller C, Kleer R, Piller FT (2015) Economic implications of 3D printing: market structure models in light of additive manufacturing revisited. *Int J Prod Econ* 164:43–56. doi:10.1016/j.ijpe.2015.02.020
- Garrett B (2014) 3D printing: new economic paradigms and strategic shifts. *Glob Policy* 5:70–75. doi:10.1111/1758-5899.12119
- Costa C, Aguzzi J (2015) Temporal shape changes and future trends in European automotive design. *Mach Des* 3:256–267. doi:10.3390/machines3030256
- Gao W, Zhang Y, Ramanujan D et al (2015) The status, challenges, and future of additive manufacturing in engineering. *Comput Des* 69:65–89. doi:10.1016/j.cad.2015.04.001
- Frazier WE (2014) Metal additive manufacturing: a review. *J Mater Eng Perform* 23:1917–1928. doi:10.1007/s11665-014-0958-z
- Khajavi SH, Partanen J, Holmström J (2014) Additive manufacturing in the spare parts supply chain. *Comput Ind* 65:50–63. doi:10.1016/j.compind.2013.07.008
- Karbasian H, Tekkaya AE (2010) A review on hot stamping. *J Mater Process Technol* 210:2103–2118. doi:10.1016/j.jmatprotec.2010.07.019
- Monzón MD, Ortega Z, Martínez A, Ortega F (2015) Standardization in additive manufacturing: activities carried out by international organizations and projects. *Int J Adv Manuf Technol* 76:1111–1121. doi:10.1007/s00170-014-6334-1
- Baumers M, Dickens P, Tuck C, Hague R (2015) The cost of additive manufacturing: machine productivity, economies of scale and technology-push. *Technol Forecast Soc Change*. doi:10.1016/j.techfore.2015.02.015
- Mellor S, Hao L, Zhang D (2014) Additive manufacturing: a framework for implementation. *Int J Prod Econ* 149:194–201. doi:10.1016/j.ijpe.2013.07.008
- Craeghs T, Bechmann F, Berumen S, Kruth J-P (2010) Feedback control of layerwise laser melting using optical sensors. *Phys Procedia* 5:505–514. doi:10.1016/j.phpro.2010.08.078
- Kruth J, Mercelis P, Van Vaerenbergh J, Craeghs T (2007) Feedback control of selective laser melting. In: *Proc. 3rd Int. Conf. Adv. Res. Virtual Rapid Prototyp*. p 7
- Yasa E, Kruth J-P (2011) Application of laser re-melting on selective laser melting parts. *Adv Prod Eng Manag* 6:259–270
- Makinouchi A (1996) Sheet metal forming simulation in industry. *J Mater Process Technol* 60:19–26. doi:10.1016/0924-0136(96)02303-5
- Uddeholms AB (2013) Cold Work Tooling Tooling Application. 28
- EOS-GmbH (2011) Material data sheet EOS Maraging Steel MS1. 6
- Townsend A, Senin N, Blunt L et al (2016) Surface texture metrology for metal additive manufacturing: a review. *Precis Eng* 46:34–47. doi:10.1016/j.precisioneng.2016.06.001
- Spears TG, Gold SA (2016) In-process sensing in selective laser melting (SLM) additive manufacturing. *Integr Mater Manuf Innov* 5:1–25. doi:10.1186/s40192-016-0045-4
- Kruth J, Badrossamay M, Yasa E, et al (2010) Part and material properties in selective laser melting of metals. In: *16th Int. Symp. Electromachining*. pp 1–12
- Löber L, Flache C, Petters R et al (2013) Comparison of different post processing technologies for SLM generated 316L steel parts. *Rapid Prototyp J* 19:173–179. doi:10.1108/13552541311312166
- Ghiotti A, Bruschi S, Medea F, Hamasaiid A (2016) Tribological behavior of high thermal conductivity steels for hot stamping tools. *Tribol Int* 97:412–422. doi:10.1016/j.triboint.2016.01.024
- Rayna T, Striukova L (2014) The impact of 3D printing technologies on business model innovation. In: *Benghozi P, Krob D, Lonjon A, Panetto H (eds) Digit. Enterp. Des. {&} Manag. Proc. second Int. Conf. Digit. Enterp. Des. Manag. DED{&}M 2014*. Springer International Publishing, Cham, pp 119–132
- Grunberger T, Domrose T (2015) Direct metal laser sintering identification of process phenomena by optical in-process monitoring. *Laser Tech J* 12:45–48